NASA's DREAM2 - Evidence of Dynamic Hydrogen, Hydroxyl, and Water at the Moon
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Jeff Nee: Hello everyone. This is Jeff Nee from the Museum Alliance. I'd like to welcome you to this telecon today. Thanks to all of you for joining us and to anyone listening to the recording in the future.

Today we're talking about NASA's DREAM2 Program -- specifically the evidence of dynamic hydrogen, hydroxyl, and water on the Moon. The slides for today's presentation can be found on the Museum Alliance and NASA Nationwide sites. As always if you have any issues or questions now or in the future, you can email me at JNee@jpl.nasa.gov.

As a final reminder, please do not put us on hold even if you have to step away because some phones play holding music which can disrupt the talk. Just be sure your phone is on mute so that no noises from your end interrupt the speakers. If you'd like to do one final check that you are in fact muted, you may simply say your name into the phone right now.

Great. If you can hold your questions until all of our speakers have finished, that would be much appreciated. We will have some time for questions at the end so just make sure you have a pen and paper to write down your questions as we go. And it's always helpful to note what slide number you're referencing, too.

Remember that if you have to drop off early, this and all of our talks will be accessible on the websites. And again, you can always email us with your questions. As educators, we all know that there are no stupid questions, only missed opportunities for learning.

You'll be able to read the full bios for our speakers on the websites but as a brief introduction, our first speaker today is Nikki Whelley from the Education and Public Outreach Team for DREAM2. Nikki, you're up.

Nikki Whelley: Hi. Thanks. I just wanted to, for a few moments, talk about some of the DREAM2-supported workshops that we have coming up this summer. The first one is the Solar System Exploration Public Engagement Institute which is put on by Johns Hopkins University's Applied Physics Laboratory. It is for people who conduct programs for the public and for children. Through this workshop, or institute, participants will do hands-on activities, talk with scientists about current solar system exploration research, and tour some scientific facilities.

It's being held July 23rd through the 26th, and here at Goddard, the DREAM2 team will host the Institute for a day, talking with some of the scientists, touring some facilities, and having lunch. The Institute is currently full but if you want to be on the wait list, you can sign up online.

And then the second thing I wanted to talk to everybody about for just a moment is the International Observe the Moon Night which is an annual public worldwide event that encourages observation, appreciation, and understanding of our Moon. This year it will take place on October 20th and there are many events hosted around the globe that you can join in on or you're welcome to host your own event.

To find out more please visit moon.nasa.gov/observe. And this website is currently under construction but should be released by the end of the month. So please keep an eye out for that. That is all I have and I'll give you over to Bill.

Bill Farrell: **[Slide 1]** Thanks, Nikki. Terrific. So I'm Bill Farrell at NASA Goddard Space Flight Center. Nikki, thanks so much. And I wanted to talk a little bit today about the water story at the Moon. You may have been hearing that there's water at the Moon and you hear about different parts of it and it's kind of a complicated story. What I'd like to talk about is the evidence for this water and hydroxyl. It's very dynamic and a lot of things are going on at the Moon in the process of making this hydroxyl. So we'll talk a little bit about that.

But first I'd like to talk a little bit about DREAM2 itself and because you've been hearing about DREAM2. I'm sure you're wondering what this is all about. So I want to move onto slide two here.

[Slide 2] Let's see. Slide two shows actually our parent organization called SSERVI -- Solar System Exploration Research Virtual Institute. And this really resulted back in 2007, back when we were going back to the Moon, I think it was version 2.0. It was realized that human exploration is going to go out into this harsh environment with radiation and space plasmas, and the science side had knowledge of that and they wanted to merge - sort of get a team together where the scientists and the exploration folks could get together.

Back in 2007, that was called the NASA Lunar Science Institute; that merged then into SSERVI. And DREAM2 was a node under this umbrella SSERVI Program which really is funded in part by both science and human exploration.

[Slide 3] Now, what we study in DREAM2 -- we actually study the space environment's interaction with these airless bodies. We're a theory, modeling, and data center - and doing lab work as well - looking at this connection between that harsh environment and these dusty, silica-like surfaces -- not just at our Moon but the moons of Mars - Phobos and Deimos, and also asteroids.

Our real driving question is “How does this highly variable space environmental energy affect the airless bodies -- in particular, the volatiles that are on the body, affect the plasma that’s flowing around the body, new chemistry at the body, and how does it actually affect the surface and microstructure?” And actually in today’s talk we’re going to be getting into all of this. Our themes really kind of come together when we talk about this hydroxyl and water story at the Moon.

We love extreme events. Solar storms are kind of times when you kind of crank up all of this activity. When a coronal mass ejection occurs from the Sun that will be - the Earth has a magnetic field and blocks a lot of that energy but these exposed airless bodies feel the full brunt of those solar storms. We’re about 30 investigators from 14 partnering institutions and the lead institution is here at NASA Goddard.

[Slide 4] Our themes -- I’m on now slide four -- our themes kind of merge together. We study the exosphere which is really the collision-less atmosphere around the Moon, plasmas, space plasmas that are incident with the Moon, radiation and then the surfaces -- how is the surface affected by these external sources of energy.

And as it turns out, these are common processes that not only occur at the Moon but, as I mentioned before, Phobos and asteroids, near-Earth asteroids -- targets that exploration would be going after.

[Slide 5] And just some vital stats. That’s the next slide, slide five here of our team. I think I’ve talked a little bit about the number of team members we have -- 14 partnering institutions from California. We have folks at Berkeley and NASA Ames and all around the country are our institutions. We’ve been around for a few years. Our team so far has produced a total of about 94 papers, about 90 papers in press or published.

If you want to know more about DREAM2, our annual report is online. I have a web link for you down there, down at the bottom if you want to know more information about DREAM2 on our DREAM2 website.

[Slide 6] But I now want to talk more about the subject at hand here -- the Moon and this hydrogenation, hydroxylation, and hydration story which is really evolving. But first let's think back, think about the Moon for a second. When you think about the Moon, you don't really think of the most dynamic place in the solar system. It's a high contrast environment. When you look at pictures of high contrast, a lot of black and white but not a lot of color.

In fact there's sort of an antiquated, old look to it. When you think about Apollo and the black and white pictures and the black and white TVs, seeing the Apollo astronauts in the flight, you sort of think back really almost 50 years now.

[Slide 7] But what if I showed you the next picture, slide seven? This is sort of a new, false color picture of the Moon in the infrared. And in fact, the blue regions that you see here are the infrared signatures that focus on water and hydroxyl at the moment up at the poles. Now *that* is a different picture of the moon. That's the picture of the moon that's been developed in the last ten years. Makes it a little more interesting, doesn't it?

[Slide 8] And the reason why is because really at the microscopic level, the Moon is actually very active and dynamic. And when I mean microscopic, I mean dust grain level all the way down to the atomic level even down into the surface. So it's really at this atomic level that a lot of activity is going on.

[Slide 9] So now I'm going to go to slide nine here. What's really happening is the surface is animated by the space environment. Environmental energy in the form of solar wind plasma. Plasma is an ionized gas made up of, in the solar wind's case, mostly of protons. They hit the surface and provide energy.

Solar UV and x-rays, solar illumination comes in and actually can kick off electrons from the surface. And of course the surface is constantly bombarded by meteoric influx. The same meteors that burn up in our atmosphere, well they hit - there's no atmosphere to speak of on the Moon so they hit directly on the surface. And when they do, the surface reacts.

So the environment drives a response from the surface and that response includes a very tenuous vapor called the exosphere. In fact, it's really a collision-less atmosphere. What that basically means is that the density is so low, the atoms don't collide with each other. There's really no pressure to speak of. The atoms, though, will go up and ballistically hop along on the surface.

Now, some of these atoms and molecules that are released from the surface also get photoionized. So we actually have a very tenuous what's called exo-ionosphere. Now, because you're exposed to the solar wind which is a space plasma, you'll actually develop near surface electric fields -- plasma sheaths -- and some of these electric fields are thought to lift dust, but also the micrometeoroids coming in slamming into the surface. You'll get secondary ejecta dust grains, high velocity dust grains, coming off the surface from the initial meteoroid influx. We'll talk about examples of that in the course of this talk.

[Slide 10] So let's go onto the next slide. This is slide ten now. So prior to 2009, most lunar scientists would consider the Moon dry and anhydrous. And in fact, that showed up in a couple of contextual science reports that the National Academy did. They refer to the moon as anhydrous. Whereas now, we actually speak in terms of a water cycle.

So I guess the question you probably ask is what happened? What changed? What changed in our view? And really there are three revolutions. One was in the lab -- and we'll cover that -- one is in remote sensing -- and we'll cover that one -- and another one is in an active lunar experiment. And all three of these changed our view about the Moon as having a lot more water than we originally thought.

[Slide 11] So from an overview perspective, I'll show you slide 11 here. It really kind of shows just how dynamic the Moon is. What I'm showing you are four sources of hydrogen and hydroxyl and possibly water on the Moon.

The first source is a polar source, actually. So what I'm showing you here in this figure is – imagine a swath of terrain at midlatitudes. And there are a number of sources of volatiles. That's what we call water and carbon -- kind of these easily released species, volatiles. One is from the lunar poles where we know water exists. Water may get released and get down to the midlatitudes. We're finding more water in the samples that came back from the Moon. So there's water and OH in the mineralogy itself - more so than we had appreciated in past sample analysis.

Meteoroids come in and they actually are volatile rich. Some of them actually have amino acids. They actually land on the surface to create water and OH and really this infall can deliver material to this midlatitude range. And also the solar wind itself, the solar wind is protons. They come in and hit the surface. As it turns out, the lunar regolith is oxide rich. It's a silicon dioxide SiO_2, iron oxide FeO, sapphire Al_2O_3. Half the lunar regolith, half of that soil is actually bound oxygen. So when these hydrogens come in, you have a chance for new chemistry to create OH. So there's a lot of different sources for this volatile hydrogen and OH and possibly even water.

[Slide 12] So let's first talk about the polar source. Let's see, we're going on now to slide 12. As it turns out, the poles at the Moon - particularly in the permanently shadowed craters up at the poles - they don't get sunlight. They haven't gotten sunlight for billions of years. They are very cold. As it turns out, any water that may have been deposited on the Moon - for example, if a comet had hit the Moon - that water will thermally migrate up to the poles and be trapped up in those cold traps.

[Slide 13] So it can trap water and actually other volatile species. We know this because Lunar Reconnaissance Orbiter and LCROSS and other experiments have sensed these. But it's really from the early 60s that it was suspected - and I'm going on now to slide 13 -- it was really in the early 60s that it was suspected that the poles could trap water, that these regions were cold and water could be trapped there.

And we got a first hint that this was possible in the late 90s when Lunar Prospector flew its neutron spectrometer instrument. This instrument actually sensed energetic neutrons. Actually, what ends up happening is galactic cosmic rays hit the Moon all the time, and these galactic cosmic rays penetrate in meters deep. And when they do, they interact with the nuclei in the material, in the lunar material, and create secondary neutrons.

Now as it turns out, if there is no water or hydrogen on the surface of the Moon, those neutrons would energetically flow right out. But if you've got a layer of water, or at least a layer of hydrogen, because hydrogen is the same mass as those neutrons, those neutrons get slowed.

So what you're really looking at here in that upper left figure is the absence of neutrons because there's hydrogen there. It's almost like the water or the hydrogen is being backlit by the energetic neutrons.

Now, Lunar Reconnaissance Orbiter - LRO - flew their own version of a neutron detector and they also found these neutron-suppressed regions. A strong one was in Cabeus crater. They've calculated that maybe the water content - it's not a lot of water, but a fair amount - maybe up to about 500 parts per million, maybe in some places maybe up in even up to a percent or so.

So this sort of helped set the stage for the idea that there is water up in these cold traps. Now, at this point it's only hydrogen. At this point, no one knew that it was truly water and it might simply be hydrogen.

[Slide 14] Now I'm moving onto slide 14. Lunar Reconnaissance Orbiter team, the team there did a couple different things. First off, the figure on the left shows a model of the water thermal stability based on LRO's Diviner instrument. Now, Diviner measures temperatures - surface temperatures and a little bit into the subsurface - and based on their measurements, Dave Paige and his colleagues made a prediction map, if you will, of where you would expect to see water frost.

And they found it that in these - this is for the south pole of the Moon - in these permanently shadowed craters at the south pole of the Moon. They could actually be cold enough to have water frost right at the very surface.

Then in other places where you see that red, you can get water buried down a few, I believe, it’s a few millimeters or so in those regions. And sure enough, LRO also has a UV sensor and by looking at the right bands in the UV, that UV instrument was able to actually psych out, find those regions of water.

You can see the blue there - now we’re looking at the right-hand figure there - the blue represents regions where you’re finding this water frost on the surface. The black regions represent where it’s really cold in those permanently shadowed craters. So the black regions represent cold regions. You can see the water frost represented in blue overlie on some of the black. So that’s telling you that the frost and the cold regions sort of line up here. So LRO really made some great advances.

[Slide 15] Now I’m moving onto slide let’s see, slide 15. So in fact if you actually combine these two sets of measurements, we may have two forms of water in the pole. One is this deeper hydrogen - which I’ll let you know in a second actually really is water - this hydrogen reservoir observed by neutron spectroscopy. We know that it goes at least a meter deep but we also, based on the neutron signatures, suggest that maybe there’s a dry layer in the first ten centimeters.

So in the permanently shadowed craters, we have a dry layer and then this water, this deeper hydrogen layer. Then on top of the dry layer at the very top maybe 100 microns or so there’s this frost. So you have frost at the very tippy top, dry, then this bulk reservoir, all right? Very interesting. So by mixing and matching these instruments, you’re actually starting to get a little bit at the stratigraphy if you will of the water in these poles, but it’s very inferred at this point.

[Slide 16] Now, the proof of the pudding came in revolution number one. Now, remember I said there were three revolutions that changed our view? Revolution number one is the LCROSS Impact Experiment in 2009. What happened here is a Centaur booster [rocket went along with LCROSS]. And the Centaur booster was driven into Cabeus crater - one of these permanently shadowed craters. And what it found is that the plume was water rich. In fact, the water was actually 5% weight of the material that was lifted off that crater floor. Actually that water percentage is actually much higher than the neutron [experiment found. The water was in the form of a vapor. It was also in the form of icy dust.] So that was what really changed our view.

We then knew for sure water was at the bottom of these permanently shadowed craters, that hydrogen reservoir that we've been referring to really is probably a water reservoir. So this was an amazing experiment, I thought, just a terrific thing.

[Slide 17] Now, getting back to this distribution of the deep hydrogen - so I'm looking now at slide number 17. A couple things: First off, the distribution of this deeper hydrogen reservoir, this reservoir actually doesn't lie exactly concentric around the pole of the moon. As it turns out, it actually is somewhat elongated and actually elongated in the south pole towards Cabeus crater. Actually if you looked in the north pole, it's also elongated as well to a point antipodal, or at the opposite longitude, of Cabeus crater.

Matt Siegler came up with an idea just a couple years ago that possibly what happened was that maybe three and a half billion years ago the spin axis of the Moon was actually at Cabeus crater and its antipodal point at the north pole. And at that time, either a comet hit, there was just a lot of water introduced into the Moon environment. It got caught in the cold traps and then over time the poles wandered back to the positions where they are now, creating this elongated streak in both the north and south pole of the deeper hydrogen reservoir. I call it a Cabeus shift in the hydrogen reservoir.

[Slide 18] What's interesting though is if you go to the next slide and look at the LRO UV signature of the water frost - that frost right at the tippy top - you don't see that Cabeus shift. In fact, it lies mostly concentric - with some notable exceptions - mostly concentric around the poles.

[Slide 19] So in fact if you go back from slide 17 to slide 19, 17 to 19, you see that the distribution is very different. Actually, I'll say a few words about slide 18. This is the LEND data of this deeper hydrogen reservoir which also shows the Cabeus shift. LEND is the neutron detector on LRO so its data look somewhat similar to the Lunar Prospector data. So slide 17 and slide 18 are looking at that deeper reservoir, while slide 19 is looking at the frost.

[Slide 20] Slide 20, LRO also had a LIDAR. It's also looking at the frost and it too sees the frost mostly concentric around the pole. Doesn't see that shift towards Cabeus - in this figure Cabeus would be in the upper lefthand corner. And there's a little frost there but nothing remarkable.

So what this suggests if you look at the distribution of the frost compared to the deeper hydrogen reservoir, it's as if they are not entirely connected. And why that's important is if in the future you ever want to prospect for water as a resource, the frost could be sort of a red herring and a little deceiving. What it also might mean is the process that creates the frost might be different than the process that creates the deeper hydrogen reservoir.

So that's actually sort of the water story from an observational point of view. One of the things that we've been looking at on our DREAM2 team is how does this water interact with the space environment, and in particular the frost.

[Slide 21] That top layer is directly exposed to the dust and to the meteors that come in. It's exposed to the solar wind - not directly but can get exposed to the solar wind. So as a consequence, those represent environmental losses to the polar water frost. So you might actually expect the frost to over time either be dwindling because of either the solar wind eroding through sputtering because it's plasma sputtering the frost off, or small meteoroids, micrometeoroids coming in and vaporizing the frost.

What's interesting is the frost, at least over the time scale of what LRO has been looking at, doesn't seem to be eroding all that much. So if it's in dynamic equilibrium, the losses might be telling you something about the source.

[Slide 22] Just to give you an example of some of our models, this is a model we put out back a few years ago where we looked in the polar craters, we looked at the micrometeoroid environment. What you're seeing here, we were looking at 100 meter by 100 meter swath of a model meteoric flux. We used the Grün model of meteoric flux. We looked over about I think it was ten days, a million seconds. And basically in a million seconds if you looked across that 100-meter region, you would expect a lot of micrometeoroids to impact that little piece of terrain, that 100-meter terrain. In fact what you're seeing here based on the Grün model are the various - each little vertical slice there represents a puff from the surface of the meteoroid vapor and the water that's leaving the surface.

Now, what's interesting is the meteoroids come in and a lot of the water actually leaves energetic enough to escape the Moon. Being faster, the water molecules would be leaving faster than the escape speed of the Moon which is about 2.2 kilometers a second. However some of them, a lot of them actually, don't escape and are bounded. They come back down.

[Slide 23] So if you go to slide 23, it shows you what happens. You have water leaving the poles and then they come down someplace at midlatitudes. And then what they would do is try to thermally migrate back up towards the poles. Because the water resides on the surface, it will desorb and start migrating towards the surface, back up towards the polar cold trap. So you can actually think of this as almost like a little mini water cycle.

[Slide 24] Here's an example in slide 24 of one of our models. Let me see, slide 24 here, one of our models. This is around a 20 by 20 kilometer crater. We're actually predicting where the water would fall based on the meteoric influx into the crater. You can see you get a water buildup near the crater's lip but then it would dwindle away.

[Slide 25] Actually if you go to slide 25, this shows you the water that's plasma sputtered and impact vaporized out to midlatitudes at the lunar surface. So this suggests that - at least our model suggests that - the water in the poles could be a source for water and hydroxyl down at lower latitudes. Due to this – we call this the spillage effect - the space environment energizes the surface and causes the water to be transported down to lower latitudes.

[Slide 26] Now again, one curious thing about this is if you have these losses of the water frost, which include plasma sputtering and impact vaporization - and we know we can quantify those losses, we can put a number to them - if you're in dynamic equilibrium, that means there has to be a dynamic source for the water coming into the poles making that frost. That means that that frost is sort of like a dynamic living thing right now. We know it's being lost at about 10^8 waters per meter squared per second. There has to be some other source active to compensate.

Now, one source might be the meteoroids themselves. The meteoroids can have water. We'll talk about this in a few minutes. They'll impact. A lot of that water will be promptly lost in the impact vaporization process to generate a 4,000 degree kelvin plume. But some of the water that's not as energized would still stay local to the region.

Solar wind may also implant down at midlatitudes, generate water that way. And that water may migrate up. That might also be a source as well. We'll talk about these two sources later on in the talk.

[Slide 27] So the key questions regarding polar water is where did the deep water, the deep hydrogen reservoir detected in the neutron spectrometers, where did that come from? Was it from a past comet? Is Siegler's idea, this polar wanderer, the H distribution, correct? Can that account for this Cabeus shift that we are seeing? I mean, it's very provocative, a really cool idea.

How deep is this hydrogen layer, this deep reservoir? We only know what the neutrons tell us but they can only go down to about a meter. It might go on even deeper than that.

This polar frost, this thin veneer, how is that connected to the deeper water reservoir, hydrogen reservoir? And if they are not connected and they have different sources, what are those different sources?

So the next three questions sort of are all kind of combined together. Could some kind of to-be-defined process at midlatitudes create water and have those waters migrate up to the poles to deposit in the cold traps? In other words, does water flow from lower latitudes up to the permanently shadowed regions? An early paper in the early 2000s suggested it did but I'm not sure we're seeing the evidence for it.

Conversely, does water flow out of the poles and land down at midlatitudes? Is there water infall, water being shot out from the poles? Or to say it in another way, how dynamic is that frost deposit in the PSR [Permanently Shadowed Regions] floors which are really restating the two other questions above. And in that case, how global is this water cycle? Is it local or if waters are being shot out and they're migrating back up, I mean it suggests it sounds like a global water cycle.

[Slide 28] So we really need something to get into these permanently shadowed craters to do all that. And I just want to show a little cartoon here. Here's slide 28 where you'd have a strong cycle in the reservoir, they are connected. So you have these migrating species. Solar wind, which are protons coming in and making water at midlatitudes that would migrate up to form the frost. Then micrometeoroids would come in and the frost gets kicked back out. You could have like a cycle. The deep reservoir would be accessible and it's connected to the frost. That's one way of looking at this.

[Slide 29] But if you go to the next slide, you might actually have a different picture whereby the frost and the deep hydrogen reservoir are disconnected. As I said, it's only about ten centimeters separating the two. What's interesting about ten centimeters is it's far enough to actually block just thermal transport, but it's actually penetrable by larger meteoroids. Larger meteoroids can actually get through ten centimeters. So there may be perforations, if you will, that allow the modern dynamic volatile cycle that we think might be going on to interact with this deep hydrogen water reservoir that we know is there thanks to LCROSS.

[Slide 30] So okay. Slide 30. Let's just take a moment here. I mean, honestly think about this - we are now talking about a possible water cycle at the

Moon. Scientists are actively pursuing an understanding of this. We wouldn't have even thought like this ten years ago.

We also think, because of the Moon, that this could be happening at Mercury because we know based on the Messenger mission that there is water ice in the poles there. In fact, there's more water ice at Mercury and their cold poles than at the Moon. And this may be going on at Ceres, the big asteroid, as well. I mean, it's kind of amazing. Sort of like I say, it's revolutionary in thinking.

[Slide 31] So let's go onto source number two here - the minerology. And I have to admit I'm not an expert in this but I read some of the papers, so I'll share with you my insights on these. It doesn't mean I'm the expert in this.

[Slide 32] But I will call this the second revolution. And that is the Apollo samples -- the gift that keeps on giving.

You know, the Apollo samples came back and we did an initial study of those, grabbing samples, and it was thought that from the samples that we were looking at that the Moon was pretty dry - not a whole lot of hydrogen in it, maybe 40 to 60 parts per million.

But now using more modern analysis and sort of in some sense we've got a lot of samples, a better sample selection, we're finding a lot higher levels of OH and water in some of the samples. For example, there's enhanced water levels preserved in some of the volcanic glasses that came out in Alberto Saal's paper in 2008.

A few years after that there's hydroxyl, high levels of hydroxyl in certain what's called apatite mineralogy which is from samples that were picked because they came from the end of the lunar magmatic period. And it looks like the water in some of the products were the last things to distill out when the magma was cooling. And so you have the waters kind of trapped in sort of the material that didn't quite completely distill into the magma. So they were looking at those samples. High water samples there.

There's also high water samples and high OH levels in agglutinates. Agglutinates are a fancy name for solidified impact melts. When micrometeoroids come in, they not only hit and make a [4,000K] plume - little micro plume - not only do they make a vapor but they actually melt, make a melt in the lunar soil. The fancy name for it is an agglutinate. But just think of it as a glassy melt that's been created by a micrometeoroid impact.

[Slide 33] Let's first talk about where maybe some of this water came from in ancient times, back during the magmatic period. My colleagues at another SSERVI institute, Jessica Barnes and Dave Kring, suggested that maybe that water came in from asteroids and not comets. They looked at the space on isotopic compositional analysis from some samples and they think that during the magmatic period we were bombarded by asteroids large and small and that kind of gave the water content that we're seeing in some of the mineralogy - particularly from these early periods.

[Slide 34] Now moving onto slide 34 though, I'd like to talk a little bit about the agglutinates. They're more modern. That could be happening now. In particular, lab analysis of some of the agglutinates, from some of the samples that were returned with the Apollo missions, found OH, high OH levels, in this glass. Not only that, this is what's wild - the hydrogen in those glasses appeared to have a D-to-H ratio - a Deuterium-to-hydrogen ratio - that is similar to the solar wind.

So it's telling you, if you think about this, that the solar wind is implanting the hydrogen that is somehow getting embedded into the melt during a meteoric impact. That means two pieces of the space environment - the solar wind and the micrometeoroids - are working together to make this OH. So it's just wild. The space environment is sculpting this water story, as we're seeing it in the samples.

[Slide 35] So some of the key questions - and again, these key questions are sort of my questions, also though other scientists have these questions as well - but some of these key questions are what was the water content when the Moon was formed? It seems to be higher than originally thought. And if water was delivered to the Moon, what does that say about the Earth during this period many billions of years ago - three and a half billion years ago?

Then in a more modern perspective, this OH that's created in the impact process that forms the agglutinates, how is that - what's the formula there? Where is that hydrogen coming from? How exactly does that happen? What is the sequence of events? We just don't know. Is that OH creation process by impacts going on today as micrometeoroids impact the Moon? Because you know, the Moon is still being impacted today. We're making these agglutinates now. And if that sample is correct, chances are the answer to that is yes.

Now, a lot of this water we don't think of as dynamic. It's trapped in the mineralogy into the matrix of the crystal. But the agglutinates may be dynamic and we'll talk - the OH and the agglutinates may be dynamic since the meteoric impacts are occurring now. We'll talk more about that.

[Slide 36] In fact, that sort of feeds forward into the next source of water. If you look at slide 36, which is meteoric infall. In fact, there's sort of a nice

Venn overlap of these two topics, the agglutinate story and the meteoric infall story.

[Slide 37] In particular, the Moon is constantly bombarded by projectiles large and small. In fact the micrometeoroids are coming in at about ten kilometers a second or so in their peak distribution. But when you get a meteor stream, that can actually go up to about 35, 40 kilometers a second. Some of these chunks originated from asteroids. They're delivering volatiles to the surface. Water - actually some of the meteoric samples have amino acids. And when they hit, they create this [4000] kelvin impact plume. So you get a prompt loss of some of the material. It's almost like a little oven.

But some of the volatiles that aren't seeing the total effect of the plume actually can hang around and stay on the surface. Again, as I mentioned, some of these can be water and hydrocarbon rich - particularly if the chunks come from the outer main belt.

[Slide 38] So just to give you an example here, this the Grün model. And so what I'm showing here is the mass of the impactors in grams. There's a log of mass down on the X axis. Along the Y axis is the log of the flux. What this basically says is a lot of little things are constantly raining in on the Moon while the big stuff happens more occasionally. It has a much lower flux level.

But let's consider one micron impacts and below. And so I've sort of crossed -- this is in slide 38 -- sort of have a cross at the one micron point. You can also see I also threw in some agglutinate pictures here for you. So this is the result of the [4000K] impact. And again, we know these meteoroids are there because they hit the Earth all the time. They burn up in our atmosphere. But the Moon, they just hit the surface.

So you would expect a one micron-sized meteoric strike, one micron or below in one square meter -- so one three foot [square] -- every three hours. Or to think of the flux another way, if you had 100 meter by 100 area - the size of a football field, say - you might expect one [per] second, a one micron impact onto a surface of the Moon. So there's a lot of little stuff hitting the moon all the time.

[Slide 39] Now, let's draw an analog here to our friend, Vesta. Vesta is an airless body. It's an asteroid way out. And just to show you how potent infall can be, I'm showing you some data here from the Dawn mission from an IR, from an infrared, spectrometer. The plot on the X axis is the reflectance that is indicative of soil brightness. And this is on slide 39. And on the Y axis I'm showing you the 2.8 micron band. And as it turns out, hydroxyl has a vibrational state at 2.8 microns.

So when you look if there's a lot of hydroxyl in your surface, you'll see an absorption feature at 2.8 microns like a bite out in your spectra at 2.8 microns due to hydroxyl. If you don't have any hydroxyl, you won't see any dip. But a lot of hydroxyl, you'll see a band depth, a band bite out in your spectra around 2.8 microns. So their plotting reflectance is a function of basically hydroxyl content.

And what you see is as the material gets darker as indicted by the lower reflectance in the soil brightness, that's where the hydroxyl content is actually going up. So the darker material the hydroxyl content is going up and as Tom McCord suggested, this means that infall - which is they think related to the darker material - meteoric infall is delivering hydroxyl to the surface.

[Slide 40] So it's happening at Vesta. The question is it happening at the Moon. And back in 1991, Morgan and Shemansky - Tom Morgan down the hall here at NASA Goddard - suggested that if you looked at the meteoric influx and if you assumed those meteors had about 5% water in them, you might expect about 10^9 waters per meters squared per second to be delivered by the small micrometeoroids. It's actually a fair amount of water.

Now, a lot of that would be promptly lost because as they're delivered as I mentioned there's an immediate vaporization because of the [4000] degree kelvin impact. But a lot of them would hang around too. So it's one way of getting water to the Moon.

[Slide 41] And we know, thanks to the LADEE mission which went up in 2013 - LADEE mission stands for Lunar Atmosphere and Dust Environment Explorer - I'm surprised I can still do that - the LADEE mission 2013… "Atmosphere" in this case they really mean "Exosphere" but the acronym would read very even more crazy if you put an E there, LEDEE. So they called it LADEE and just lived with the "Atmosphere."

But there was a dust detector and the dust detector detected these micrometeoroids coming in all the time. In fact, what the dust detector sensed wasn't the micrometeoroid itself. It actually detected its secondary impact. The micrometeoroid comes in and when it comes in it ejects a cloud of secondary particulates that leave the surface relatively fast -- less than a kilometer a second or so -- from the Moon - and LADEE would intercept those secondary particulates.

But based on that, they could actually figure out where the flux of micrometeoroids were hitting. And actually they were tended to be hitting just towards the velocity vector of the Moon, in the velocity vector of the Moon which actually is just after dawn. So you tend to get a lot of micrometeoroids hitting at that time.

So this was a real big find because in some sense we always knew that micrometeoroids were working the surface, but the duct detector - really probably one of the big finds was that they really reemphasized just how warped that surface is from the micrometeoroids.

[Slide 42] And LADEE also had a UV spectrometer on board. It just so happened it was during the Geminids meteor stream that it was up. So it made a set of measurements before Geminids and made a set of measurements during and immediately after Geminids. They saw a greater release in the exosphere, the atmosphere of the Moon, of species that you typically get in the regolith like titanium and iron and aluminum - all of the stuff that the surface is made of, the part of the oxides like iron oxide, the iron was released.

But one thing that they found was OH. OH was kicked off at the same time along with all of these oxides, which is telling you that the oxygen that the hydroxyl is somehow part of the impact vaporization process.

[Slide 43] So I then bring up - so this is back in 2015 when this was presented. I then bring up this 2012 paper where we found the hydroxyl in the melt. It’s got to tell you that somehow these two hydroxyl observations associated with the meteoric processes have to be related. You’re seeing the hydroxyl in the melt that’s of solar wind origin possibly. And then you’re seeing hydroxyl in the exosphere during the meteor stream. It’s just we don’t know how they’re related but they got to be related. Somehow that hydroxyl is being formed in the process and sticking in the melt but also getting out through the vapor.

And I was talking to Tony Colaprete - going back to slide 42 -- about his observations. I said are these solar wind type hydrogens or are they hydrogens associated with the meteor stream and he said he just doesn't know. So we don't really know but there's something curious going on here.

[Slide 44] So now I'm going to slide 44. And just to make it even more convoluted, let's go back up to the polar craters and the water frost. Randy Gladstone in 2011 presented this really provocative idea. It was like the last paragraph of his paper where he's looking at the water frost and the UV. And he said goodness, couldn't that water frost just simply be generated locally by micrometeoroids? The micrometeoroids are coming in. They're delivering the water. The water sticks because it's cold.

Now, it doesn't build up because we have these other losses. You have UV losses, you have losses by plasma, you have losses by the micrometeoroids themselves. The same micrometeoroids that deliver the water can also make it release it when they impact at some other time. Or part of it's lost through prompt vaporization.

So that would mean that this whole frost again might be a red herring compared to that the reservoir because it all just be locally generated.

[Slide 45] So this brings us to slide 45, which is sort of like the third view of the water cycle, which is: there is no cycle. It's all released from a frost perspective. It's all delivered locally by micrometeoroids. And again, there is some prompt loss. The 4000 degree plume maybe kicks some water off in midlatitudes like some of our models show. But a lot of it stays local.

So this would be probably the most uninteresting possibility for the frost but it would then suggest that maybe the deeper hydrogen reservoir is delivered by a comet back in the past and then sort of micrometeoroids are delivering the tenuous layer now.

[Slide 46] So again, key questions, a lot of things we don’t know about this infall. Does the infall of micrometeoroids continually deliver OH and water to the Moon like it does at Vesta? How is the agglutinate water - the water trapped in that melt - connected to that exospheric water that we’re seeing or OH that we’re seeing? They somehow got to be related. Are they complementary manifestations of the same impact-related process?

And again going back to Randy Gladstone’s idea, is this water frost really at the poles simply a local impact process and not even related to the big hydrogen reservoirs?

[Slide 47] So, a lot of questions to be answered there. Which brings us to the fourth way in which hydrogen and water is delivered, and that is the solar wind. The solar wind of course is - we’ll talk a little more about this - is made up of protons and its direct energetic protons, they’re hitting this oxide-rich regolith and it’s one way to make hydrogen.

[Slide 48] And why this really came up is back in 2009 - and this is I think revolution number three - remote sensing in the IR. The IR folks from three different instrument teams got together and started comparing lunar observations and found that in fact there is a 2.8 micron hydroxyl absorption feature looking at the Moon. In fact, three different spacecraft instruments verified this. The three papers came out in tandem.

As I show you here on the lower left is what one of these three micron spectra sort of look like in the EPOXI data - Jessica Sunshine’s paper - where at 2.8 micron you get this real distinct - it’s called a checkmark-like feature in the spectra. That’s why it’s so distinct at this hydroxyl OH feature.

But one of the things they found is that when the surface warmed up, the hydroxyl feature sort of disappeared. So there might even be a dynamic aspect to this hydrogen that's coming into the Moon where it can get trapped up in cooler regions like at the poles and the terminators but may disappear when the surface warms up. So it might be very loosely bound hydrogen.

[Slide 49] Because of that, the number one suspect, the prime suspect was the solar wind. Of course, the solar wind is this ionized gas. It's a plasma. Plasma is the fourth state of matter. In fact actually most of our mass in the universe is plasma. Good example is our Sun is mostly composed of plasma; it's protons and electrons streaming out at 400 kilometers a second. Or if you like to speak in terms of electron volts, it's about 1,000 electron volts. But we'll stick with 400 kilometers a second as a nice speed.

So this stuff is very fast an incident at the Moon. It has a temperature near 100,000 degrees kelvin. And any airless body is an obstacle to this conductive plasma fluid, basically, that's seeping out of the Sun.

[Slide 50] In fact you can actually talk about the solar wind protons and how the surface converts them. The surface not only makes the surface OH like Jessica Sunshine and Carly Peters and Roger Clark found, but it also - about a couple percent of it actually gets immediately reflected back off this proton so it can't get in.

About anywhere from 10 to 40% come off as energetic hydrogen, so it gets back scattered hydrogen. A lot of it comes off, maybe up to as much as 50%, comes off as hydrogen molecules. Two hydrogens get implanted into the surface and they find each other and leave the surface as H_2. So the surface is actually a chemical converting surface. And LADEE found that there's methane coming off the surface. So some of these hydrogens may team up and find a solar wind carbon and leave the surface as CH_4.

What this tells you is that this oxide rich soil, this regolith, this dusty regolith, is actually a big chemical conversion surface and you get - the solar wind implants the hydrogen, but all different kinds of products come out including hydrogen molecules, methane, possibly OH and water.

[Slide 51] Now what I'm showing you here in slide 51 is a map of this hydroxyl feature -- the 2.8 micron band depth feature. And you can see - you don't really see a whole lot of it midlatitudes or at low latitudes where it's warm, where it tends to get warm during the course of a lunar day. But you do see it up at high latitudes. Li and Milliken converted the hydroxyl band depth to a water percentage and they were getting upwards of about 1,000 parts per million. So it's not a lot of hydroxyl but it's a measurable amount in the IR.

[Slide 52] They also looked at this OH feature and looked at - in the next slide - the diurnal surface variation of this hydrogen. They found that, in fact, at local noon you tended to get the lowest values. Particularly you can see it up in the right-hand side of the figure up in the north regions where at local noon the hydroxyl values were much lower than at local morning and local afternoon where it's cooler.

[Slide 53] Now, what do we think is happening in the soil? This is what we *think* is happening; we don't *know* that it's happening. But what we think is happening is: the solar wind is coming in, the protons are coming in. They immediately find an electron and now they're implanted hydrogen in this oxide crystal matrix. Then the hydrogens start to diffuse out and they diffuse out by jumping from oxygen to oxygen. And the only way, at least in 2006, that they thought they could leave the surface is that the two hydrogens will find each other and leave as a hydrogen molecule, an H_2.

[Slide 54] But what's interesting is that as this hydrogen diffuses through the crystal, if the crystal is damaged you will tend to get much slower diffusion. In fact, what happens is as you get defects, the hydrogen will tend to get hung up and trapped in its diffusion. And in fact, the solar wind implanting creates defects. The same solar wind that's implanting and making the hydrogen, that energetic hydrogen coming in tears up the surface, tears up the regolith by creating at least two vacancies per incident ion.

So you'll actually get a lot of damage with the solar wind and the damage is in sense self-fortifying for making the H. So micrometeoroids and the solar wind itself creates defects in the surface to hinder the hydrogen. And we know that the surface is weathered in this way, again thanks to lunar samples. And Sarah Noble, who's part of our DREAM2 team, what she does is she looks at these with a transmission electron microscopy. She will look at these samples and she can see as you see in this figure in the lower left you can see the rims, the top couple hundred nanometers is all an amorphous kind of material compared to the core. And actually there some iron blebs in this as well.

[Slide 55] So the surface gets weathered being exposed and this hinders the diffusion. Fink et al in 1995, they actually looked at hydrogen diffusion in irradiated silica and found that the diffusion coefficients can drop by about a factor of 10^5 compared to the hydrogen diffusion in non-irradiated silica.

[Slide 56] So one of the things that we've been doing on DREAM 2 then is modeling this process. We've been using a Fink-like diffusion coefficients and looking at solar wind implantation and making model maps. And you can see that our model maps here - and this is OJ Orenthal Tucker across the hall here - has been making these maps. You see they sort of match up to some of the observations. So it suggests that maybe this hindered hydrogen diffusion modeling may be correct. But again, some of this still has to be tested.

[Slide 57] So a possible solar wind recipe for solar wind to create water is that the solar wind implants protons, creates damage. The damage itself generally slows down the outgassing of the hydrogen, the solar wind hydrogen, that's been implanted. So you get slow diffusion. You form these meta stable hydroxyls around the broken bonds of the oxygen.

Once we have the hydroxyls in the surface, micrometeoroids - there's our friend again - the micrometeoroids can impact and with the [4000] degree kelvin flash they can possibly make water. Or the hydroxyls themselves might find each other and when an OH merges up with an OH, you might get water through a process called recombinant absorption. My colleagues down at Georgia Tech have been talking about this, making water thermally.

So hopefully you're getting the point here though, that it's getting very complicated [determining] where hydrogenation - where you're implanting hydrogen - begins and ends, and where hydroxylation - making OH - begins and ends, and where hydration begins and ends. I mean, the space environment is sort of smearing the boundaries on these processes and making the boundaries of hydrogenation, hydroxylation, and hydration somewhat amorphous.

[Slide 58] So we're getting near the end here but key questions about the solar wind hydroxylation and water is what are the chemical pathways for the implanted hydrogen in the surface? Are we missing any? Like gosh, methane sort of came out of the blue. I wouldn't have thought of methane. You know, carbons and hydrogens finding each other. So there might be others, too.

What is the form of the hydroxyl in the surface? This is really a subject a few of us discuss. Is it really this lightly bonded OH pair that's sort of metastable or is it a strongly covalent bond? Because that may have something to do with how you release it from the surface.

Again, it gets back to this idea of where does hydrogenation end and where does hydroxylation begin.

And then given the OH, can water be generated and released from mid-latitudes - from the mid-latitude lunar surface to hop up and feed the poles. So for having hydroxyl down at lower latitudes is that somehow connected to the poles.

And what role do impactors play in all this? And again, that's sort of a kind of a theme throughout the last three different subject areas we've been talking about. Impactors seem to be sort of a wild card here.

And if there's a lot of water being created through processes at the surface in midlatitudes, why aren't we seeing it in the exosphere?

So far we've got this narrative about the OH. We got a great narrative about the hydrogen and the hydroxyl. I mean we see that. We see water in the poles. But at midlatitudes we are not seeing a lot of water in the exosphere.

[Slide 59] And just taking a picture here, you have the water at midlatitudes that's being created expected to sort of bounce along the surface kind of thermally migrate in sort of a Brownian motion up to the poles. We know hydrogen molecules do this. The LRO/LAMP has seen the thermal hydrogen cloud - molecular cloud around the Moon but, we're not seeing the water cloud.

So a lot of hydrogen molecules are being created, but not so much the OH and the water. So it's telling you that the recipe, if it's there, maybe isn't quite as efficient.

If you go back to Slide 57, the recipe isn't quite as efficient as we think it is. Now I'm up here at Slide 59 now.

[Slide 60] So, where is this exospheric water? I'm up to Slide 60. If mostly solar wind is converting, it seems most of the solar wind is converting to H2 and not to water.

And again, the LADEE team has reported if there was water, they would see it. But they're seeing impact events but not in nominal periods. So, where is that water?

[Slide 61] So to conclude, for the modern Moon, stated again, where hydrogenation, hydroxylation and hydration, where they sort of all begin and end sort of blends together, really because of the space environment.

We see incoming solar wind protons. We see incoming micrometeoroid effects. LADEE saw that. We see the OH in the surface and it's dynamic, at least over the time scale of a lunar rotation. We see H_2 in the lunar exosphere. We see water in the lunar poles really revealed by a dynamic active experiment.

We see OH in midlatitudes during meteor events up in the exosphere, LADEE saw that. But we do not see a lot of water at the surface in the exosphere, at midlatitudes, during nominal times.

[Slide 62] [Slide 63] [Slide 64] Because of that - going to Slide 62, 63, and 64 - we do not know which of these scenarios is correct. We somehow need to get our hands around this cycle and what might be a very tenuous water flow in and out of the polar cold traps.

So that's basically the talk right here. I think I'm about four minutes over. If I leave you with those three illustrations, three possible scenarios for the water cycle at the Moon. Anyway I guess, hopefully there time to still entertain questions.

Jeff Nee: Thanks Bill. That was great. And yes, we have time as long as you have time. I had a quick, just a fact check thing. On Slide 37 you said 400K but your slide said 4000K. Which one is it?

Bill Farrell: Go with the slide. Go with the slide. When my mouth gets going my mouth can sometimes get disconnected from my brain. And so yes, 4000 degrees. Those impact plumes are typically - other people have modeled them about 4000 degrees kelvin or so, yikes. So not 400K.

400K is the peak temperature at the surface of the Moon at the subsolar point. So if I mentioned 400K there is that sometimes 400K, that is the peak temperature at the surface of the Moon, just through thermal insulation effects.

So like at the subsolar point, the peak temperature nominally is 400 degrees kelvin. When you have an impactor you then create this temporary 4000 degree kelvin, little mini vapor cloud.

Jeff Nee: Great, thanks. And people know that they should interrupt me if they have a question.

Adrienne Provenzano: Yes hi, this is Adrienne Provenzano. I'm a Solar System Ambassador. And I'm curious about how your research is having impacts on - I didn't mean the pun there - but what effect it has in terms of humans returning to the Moon or even having landers? I mean how is this having an impact on what's being done in terms of those plans?

Bill Farrell: Yes, that's a great question. I can tell you in 2008 there was a report by the National Academies called The Scientific Context for the Exploration of the Moon, the SCEM Report.

And there they listed all the top priorities of what we want to do if we could do science on the Moon. In that report they refer to the Moon as anhydrous. One of the chapters was "The Anhydrous Moon."

They did talk about dust. They did talk about an exosphere but they didn't talk about anything like this.

So in the last year there have been two different groups that have reexamined the SCEM Report and updated it. Because there's this feeling of we may be going back to the Moon.

And this volatile cycle, the hydrogen story has now propagated up to one of the top things to investigate at the Moon. So this is sort of getting at the volatile story. The water story on the Moon has now percolated right up.

Exploration [NASA's Human Exploration and Operations Mission Directorate] is interested in it because in particular that reservoir up at the poles, that reservoir they think might be tapped for fuel, for in-situ utilization of resources. So if there's water at the Moon they're thinking that they might want to tap it.

Now, you know the people in Exploration, they want to know how much and how deep because that's important for prospecting and mining.

From my perspective I actually want to know is the resource renewable. Because that actually makes a difference be whether that water at the poles is a Georgia Pine.

I mean if we knew it was going to renew itself every 200 years, sure, draw it out and use it all you want. We'll make more. Or is it more like a Sequoia where if it's from a comet it might hold the details of that particular comet. And it may be a one-time thing or once in a billion year sort of thing. In which case you might be more hesitant to actually access it.

So I'm more interested - and the way I couched it to the Exploration folks, the reason why you need the science of this is to understand the renewability of that resource.

So it's a great question. This stuff has percolated right up to one of the top things from both a Science and an Exploration point of view. In fact, there's something called the Strategic Knowledge Gaps which the Exploration

Groups have. And water in the polar cold traps and how water is generated is one of their top strategic knowledge gaps.

Adrienne Provenzano: And then a few years ago I was hearing a lot about this idea of Helium-3. And I haven't heard much about it recently. But does your research have any bearings on any of that? I guess that goes to the mining ideas as well?

Bill Farrell: Yes, the thought was that maybe that's coming out from the sun, Helium-3. And actually some of the same processes, cold trapping and implantation that we talk about with regular hydrogen also apply to helium and Helium-3.

So the processes are the same. The question is, is there really a big Helium-3 deposit? There's so little of it in the solar wind that it's not clear there would be a huge deposit.

So yes, you sometimes hear about it. The interest in it waxes and wanes. But certainly the processes that we're talking about would be applicable. Cold trapping, implantation, readmission by the surface, all of that stuff, those same processes are probably operating at some level.

Adrienne Provenzano: Okay, thank you.

Bill Farrell: Yes, you bet.

Jeff Nee: You know, Bill, that analogy of the Pine versus the Sequoia, that's a really great analogy. I hadn't thought about it like that and it really is all about the renewability. Because we think about water here on Earth in a totally different way than if we were to make a settlement on the Moon or some sort of lab on the Moon we would need renewable water.

Bill Farrell: Yes well in fact that's one of the reasons why the LADEE mission went ahead. I mean one of the motivations for it was on the SCEM Report it was actually number 8. Looking at the dust in the atmosphere was number 8 - the number 8 objective.

But the mission was moved up because they thought if humans really do start getting on the Moon and they start doing a lot of excavating, it's going to change the dust and atmosphere environment.

So we wanted to get an inventory of the atmosphere before humans got in there to alter the states. So yes, human presence on the fragile atmosphere will have an effect.

Jeff Nee: Then I had a quick question about Slide 54. The picture you have there, is that an Apollo sample or is that a lab picture?

Bill Farrell: Fifty-four, let's see. Fifty-four, that is actually a lab picture from an Apollo sample, I believe. From Sarah Noble's paper. Yes, and that's actually natural. You can actually see the nanophase iron in there which is characteristic of - a lot of times of an impact vapor condensate. You'll get these nanophase iron blebs, they call them.

Jeff Nee: Yes, and just as some general feedback, I loved that you inter-sliced the cartoons with the graphs. I really liked that about your presentation. That's really, really great. I also had a question about the Venn diagram on slide number 4, going all the way back. Can you give me an example of what that Venn diagram really means? Like what where are the intersections and, what kind of research is going into which section.

Bill Farrell: Yes, I can give you a great example. As a team - and we could do this under a larger team, a regular research and analysis award wouldn't do this.

Under a team we came together and asked ourselves a question. What would happen if a solar storm hit the Moon? So, that's the plasma hitting the surface so, plasma surface interactions.

So what we found is, a coronal mass ejection has about ten times the solar wind density than normal. Not only that, but the hydrogen content and the heavy ion content goes from about 2% to about 20%. So what that means is during a solar storm, the plasma sputtering will greatly increase. And plasma sputtering then kicks stuff into the exosphere.

So you have a plasma/surface/exosphere connection. And what we did with our models is we got some data of a coronal mass ejection, analyzed the sputtering, and we actually had people that were doing updated sputtering coefficients in the lab. We included them in the models to predict what would happen in the exosphere. So we connected up those three together by data analysis, modeling, lab work, and actually I think we published six papers on this, in fact. There was surface charging- yes, so we came together as a team to ask that question and it was right where all three of those merged. So, that was a good case there.

Radiation and surface interactions, galactic cosmic rays can enter the surface. But you know, some of our colleagues at New Hampshire who study radiation think that maybe when high energy radiation passes through the polar ice that you're changing the chemistry of the ice and making new products.

They have a couple of papers out on that. So there's a case where the radiation and the surface interactions connect up. We really go after this shaded area where there's overlap pretty hard.

Jeff Nee: Great, thanks. And then my last preliminary question I guess, is on Slide 9, I really like that diagram that you have. Are there any percentage numbers, even preliminary percentage numbers of how much does meteoric flux influence things? How much for solar wind plasma? Are there any percentages that we can assign to those for now?

Bill Farrell: That's a good question. Because it kind of goes back and forth. Right now I think the common - it depends on what process you're looking at.

In the exosphere there's sort of a renewed appreciation that maybe meteoric flux is driving things a lot more than they thought before the LADEE mission. The LADEE mission they found strong correlations with some of the meteor streams in the exosphere increases.

But if you're talking about hydroxylation and creating OH, we actually don't know whether it's all solar wind or whether there's a meteoric component to it. In fact you can imagine, when a micrometeoroid is coming in, delivering OH, and the meteoric and the OH that's hanging around has been delivered by meteoroids on colder regions. That is still TBD, that hydroxyl there. A lot of people are pursuing it as a solar wind source. But meteoric influx may play a role.

Or it may play a role in releasing the OHs. Stuff that's bound, the meteoric flux may release it to then create the OH layer that you're seeing.

What I actually think is happening is it's not one or the other. But there's actually a twisted - I call it a "conspiracy of the space environment." And that's why I love that dichotomy of the OH in the exosphere and then the OH that LADEE saw during the Geminids and the OH in the melt. I mean it's telling you that the solar wind and the meteoroid flux are working together to somehow make that OH. And in fact, for the OH to stick in a surface normally, you actually have to weather the surface and create defects, and micrometeoroids can do that, the solar wind can do that.

Chances are, I think it's going to be really hard to untangle them. In fact the more you look at it, you might find that they are actually working together to make their affects that they are seeing.

That's all to be unraveled. So yes, I can't say - I wouldn't want to say it's either/or because probably it could be in some cases, both.

Man: You alluded earlier to the possibility that Mercury and Vesta and other places might have similar processes. It seems for Mercury in particular, no reason why it shouldn't. Did the Messenger spacecraft provide any insight that contributes to the discussion about the commonality of these processes?

Bill Farrell: There are some common elements. The one thing that Mercury has that the Messenger spacecraft definitely found was it has a substantial magnetic field and it actually in many cases blocked the solar wind from coming in. So the solar wind component sort of drops away.

What is interesting, though, is that the ice up at the poles, the permanently shadowed regions at Mercury, is far more pronounced than at the Moon. So there's a reservoir. It may be telling us something about how that reservoir is created. But exactly what, I don't think anyone has firmly decided one way or another. There are comparisons but what's interesting is the contrasting nature, too.

It does suggest infall of meteorites, infall of comets, just general infall. Don't underestimate this ability to alter the surfaces.

Jeff Nee: That graphic on Slide 9, is that something you created or is that something we can download and print out in a bigger poster format?

Bill Farrell: That's a good question. We actually used it in our proposal. I believe it's online on our DREAM2 website. I suspect you can download and make into a poster. Let me talk to the person who made it for us. It's another scientist. Let me ask him and then get back to you on that.

Woman: Yes, I just had a question as to how Mars research is connected with what you're doing as well, since there's a different kind of atmosphere there?

Bill Farrell: Right, right. Yes, you know it's funny, when you have a collisional atmosphere like a Mars, the physics is substantially different because you are not quite as exposed.

But where MAVEN is doing a lot of work - the MAVEN spacecraft - up at the higher portion of the atmosphere, upper altitudes of the atmosphere, you actually create an exosphere, and you get gas escape. So rather than talking about a surface - as you go from a collisional to a collisionless atmosphere, you start getting into - and it's called the exobase.

You can almost think of the exobase at Mars as a surface because that's where you start getting a lot of these same phenomena with gases coming off and into free space. Somewhat similar to the Moon.

But again, the micrometeoroids don’t play as big a role because of the collisional atmosphere. And you don’t get the surface electric fields and those kinds of things.

On Phobos though, the moon of Mars, you do have many of these same processes. Should have many of those going on.

Woman: And I understand there’s some talk of having a lander on Phobos at some point.

Bill Farrell: That’s right. Yes, from an exploration perspective, Phobos looks promising because you don’t have to do all of the complex things you need to do to do descent and landing into the Martian atmosphere.

I mean decent and landing in the Martian atmosphere - you think of Mars as low pressure. It’s actually one-one hundredth the pressure of Earth. It’s actually still a very high pressure environment and very complex, the descent and landing process.

So Phobos represents a case where you could nice, gently land, put a base there and you would tell the robotics and let the robotics take all the risk getting to the surface.

Woman: Well, let’s fund it.

Man: All right any last questions?

Woman: Thank you.

Man: And of course if people have questions later, you know you're welcome to email us and we'll get them to Bill, one way or the other.

Bill Farrell: Yes, absolutely.

Man: Well thank you again everyone for joining us today. Thank you of course to Nikki and to Bill. Great talks today.

And remember everybody that all of talks are going to be recorded and posted to the member websites. And you are encouraged to share the presentation and professional development with your colleagues, including your education staff and your museum docents.

If you have further questions, like I said, just email us. My email again is jnee@jpl.nasa.gov. And as always, the most up to date information for our next telecon will be on our websites. Have a wonderful week and we hope to hear from you soon.

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